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FABRICATION AND EVALUATION OF AN OUT-OF-CORE THERMIONIC CONVERTER MODULE

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FABRICATION AND EVALUATION OF AN OUT-OF-CORE THERMIONIC CONVERTER MODULE

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Abstract

The mechanical design, fabrication procedure, and preliminary test results obtained for an out-of-core thermionic converter module, heated and cooled by heat pipes, is presented. The mechanical and thermal evaluation of critical module components, including the cermet insulator, converter end structure, and collector heat pipe in the form of a vapor fin radiator, is also discussed.

Introduction

Early in 1970 an out-of-core thermionic system study was initiated at the Lewis Research Center of NASA. The first reported results of this study is an analysis of a 350 KWe powerplant by Breitwieser and Lantz[1]. A key part of the system is a converter module mounted in the radiator, heated by a lithium-filled heat-pipe and cooled by sodium-filled heat-pipes in the form of vapor chambers. Since the feasibility of this out-of-core system is so strongly influenced by the structual feasibility and the thermal and electrical performance of the converter-radiator module, design studies were immediately initiated. Despite the wealth of information on materials corrosion, heat pipe heat transfer, and converter electrode performance doubts existed as to whether the integrated package was a sum of the individual parts. So in concert with the system analysis a design, fabrication, and a subcomponent performance evaluation of a thermionic converter module that is prototypic of the out-of-core system application was initiated in the spring of 1970.

Unfortunately it was necessary to freeze the design of the prototypic converter module before the optimization studies of a converter module for 70 to 400 KWe nuclear-thermionic systems were complete. This was of course due to the lead times required in any hardware fabrication venture. Fortunately most of the design features that were frozen a half year ago are yet consistent with the projected system applications discussed in these proceedings (Ward et al.[2]).

This paper reviews some of the ground rules used as a basis for the module design, the operating conditions considered to be of interest, the design, fabrication procedures, and the results of subcomponent evaluations.

Design Requirements

The early results of the system study indicated that the emitter temperature should be in the range of 1700° to 1800°K, and that the collector temperature should be approximately one-half of the emitter temperature. Reliability, ease of testing, fluid flow considerations, heat-pipe heat transfer, electrical isolation, and resistive losses in the electrode dictated a highly modular configuration with an emitter diameter of 2.0 to 2.5 cm and a length of 12 to 18 cm. The physical constraints in conjunction with the assumed operating conditions indicated that the power level of the converter-module should be about 1/4 kilowatt with growth to 1/2 kilowatt.

Intrinsic in the design was modularity and pretestability, not only of the module, but of the components of the module so that time and costs could be reduced while still increasing reliability.

The design was required to be prototypic not only from the point of view of cost, systems analysis, and ground test reliability, but also the design was required to meet the requirements of reliability for launching and operation in a space environment. As a result, strong mechanical stops exist in the electrode spacing element, thin or delicate members are located in protected places to avoid damage, components are arranged to avoid thermally and mechanically induced stress, and multiple chambers are included in the vapor fin radiator to provide reliability against possible meteoroid damage.

Design and Fabrication

A schematic diagram of a heat pipe heated and heat pipe cooled thermionic converter designed for in-radiator operation is shown in figure 1. The emitter material is rhenium which is chemically-vapor deposited (CVD) on a tantalum substrate. The tantalum substrate is in turn shrunk fit onto a lithium-filled, T-111 (Ta-8W-2Hf) clad heat pipe. A niobium 1% zirconium (Nb1Zr) collector is used, which is cooled by four independent sodium-filled vapor chamber fins. Four vapor chambers adequately minimize the probability of converter failure due to meteoroid puncture. The converter is relatively large, having a 10.16 cm (4 inches) long active emitter length resulting in an emitter area of 73.7 cm^2 (11.4 in.^{2}).

A picture of the heat pipe-emitter structure including the wick is shown in figure 2. The T-111 heat pipe has an O.D. of 1.9 cm (0.75 inch) and a wall thickness of 0.102 cm (0.040 inch). The annular wick structure was formed by swaging 6 wraps of 150 mesh tantalum screen. The effective wick pore size is approximately 0.0076 cm (0.003 inch). The wick O.D. is 1.661 cm (0.654 inch) leaving a lithium annulus of 0.0203 cm (0.008 inch) between the wick and the heat pipe wall.

The emitter structure consists of a tantalum sleeve on which rhenium is deposited by thermal decomposition of rhenium chloride. The O.D. of the T-111 tube and the I.D. of the tantalum sleeve were honed to less than 5 μrms finish with an interference fit of 0.0025 cm (0.001 inch). The T-111 tube and the emitter structure were shrunk fit together. The O.D. of the rhenium was then ground to 2.291 cm (0.902 inch) with a surface finish less than 10 μrms.

The heat pipe emitter structure was then vacuum fired at 1870° K and the wick was cleaned by hydrogen firing. The wick was inserted into the T-111 tube and

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final cleaning of the assembly by vacuum firing at 1820° K was performed just before filling with approximately 1.4 gm of solid lithium. The lithium fill was done in an argon environment. The heat pipe was then evacuated to 10^{-5} torr and sealed by electron beam welding.

A cermet insulator was used to electrically isolate the emitter structure from the Nb1Zr collector. The insulator was fabricated by compacting Nb spheres coated with aluminum oxide in an autoclave[3]. Part of the cermet-collector structure is shorted to the emitter to provide a continuous arc discharge at the ends of the converter. This design feature is called an igniter ring and was introduced to provide electrical stability at the lower emitter temperatures.

The end member, figure 3, is designed to accommodate thermal expansion differences between the emitter and collector structure and also acts as a thermal choke between the electrodes. This member is fabricated from 0.0127 cm (0.005 inch) thick tantalum sheet. The entire collector structure is assembled by electron beam welding.

The 0.0229 cm (0.009 inch) gap between the collector and the emitter is maintained external to the electrodes by an aluminum oxide ring positioned between the end member and the collector.

Nb1Zr was used for the vapor chamber fins (VCF) and 150 mesh tantalum screen for the wick. Each VCF is 5.08 cm (2 inches) thick, 11.43 cm (4.5 inches) wide, and 45.72 cm (18 inches) long. The wick consists of two layers of screen fastened to the outer surface by a continuous resistance weld along the outer edge. The collector O.D. has three wraps of tantalum screen with 0.0254 cm (0.010 inch) wire spacers between the screen and collector O.D. Connecting the outer screen with the collector screen are three rolls. Each roll is a tantalum tube wrapped with three layers of tantalum screen on the outside and two layers of screen on the inside interconnected by several holes in the tube. The rolls resemble small hair curlers and are forced into the space between the outer and inner wicks to form a continuous liquid return path between evaporator and condenser. The VCF assembly is electron beam welded. A picture of a partially assembled collector-radiator assembly showing the wicks and rolls in place is shown in figure 4. A final cleaning is accomplished by firing at 1120° K (850° C) in vacuum just before filling each chamber with approximately 10 gm of liquid sodium. The sodium fill was performed in an argon environment. The chamber is then evacuated to 10^{-5} torr and sealed by electron beam welding. A picture of the completed collector-radiator structure is shown in figure 5.

The final converter assembly step is accomplished by joining the collector and emitter assemblies by electron beam welds at the ends. The converter is then heated (emitter 1800° K - collector 1000° K) in a vacuum of 10^{-7} torr. After baking, cesium is loaded into the converter and the final seal at the end of the cesium tube is made by electron beam welding. A picture of the converter taken prior to introducing cesium is shown in figure 6.

Component Tests

As a prelude to the fabrication of a complete prototype in-radiator converter several of the critical subcomponents were fabricated and evaluated. The results of these evaluations are summarized below.

In regard to the emitter structure several trial rhenium chemical vapor deposition runs were made using tantalum and T-111 substrates. The purpose of the tests were twofold; to establish whether adherence of the rhenium could be obtained and to see if rhenium could be deposited with the 0001 axis exposed (Miller index)[4]. A monocrystalline rhenium emitter with 0001 crystal axis orientation exhibited excellent electrical performance in a planar research type converter at emitter temperatures in the range of 1700 to 1900° K.[5] It was felt that if, concurrent with the exploration of metallurgical integrity, the rhenium deposition process could be adapted to expose this desired crystalline orientation then a major step towards achieving practical converters with a high performance potential would have been taken.

The attempts to deposit rhenium on T-111 were unsuccessful. Apparently a reaction between chlorine and the hafnium in the tantalum alloy resulted in very poor adherence of the rhenium. No difficulty was experienced with adherence of the rhenium on the tantalum substrate and a full size emitter structure was fabricated exhibiting orientation close to the 0001 Miller index plane over the entire length.

A section of one of the Ta-Re structures was thermal soaked at 1500° C for 1000 hours to investigate diffusion phenomenon.[4] After 1000 hours a diffusion zone width of about 50 microns was observed. By extrapolation a diffusion zone width of about 50 microns (0.002 inch) could be expected after 10,000 hours of operation. This is not a significant fraction of the rhenium emitter thickness (0.020 inch) but the affected zone appears to be brittle and some axial cracking in the zone was apparent. Further investigation of bi-metal diffusion effects are necessary and such information is now being generated for a number of refractory metal combinations under a NASA sponsored contract.[6] With the success in achieving an excellent bulk orientation of the vapor deposited rhenium detailed studies of techniques for exposing the appropriate local surface orientations are now being made.[4] Since these studies are not complete the emitter used in the prototype converters has received only a cursory mechanical polish and vacuum anneal. Preliminary performance tests will be restricted to this surface finish.

A mock-up of the converter end member was built and electron bombardment heated to approximate the temperature distribution that would occur in the converter during startup and normal operation. The displacement (0.1016 cm, 0.040 inch max.) that the end member would experience in the converter was applied ten times. The end member was leak tight and flexible at the end of the test.

A single VCF was built to duplicate the ones used in the converter. The fabrication, cleaning, and fill procedures were the same as described previously. The fin was operated at surface temperature ranging from 700 to 1050° K at power inputs up to 1600 watts. The fin is now on life test at 1000° K and has accumulated over 1000 hours of operating time. At this condition the temperature drop along the length of the VCF is less than 10° C. A picture of the single chamber mounted in a test stand is shown in figure 7.

Module Tests

Based on the successful subcomponent tests described, a prototype converter was fabricated and is being tested. A photograph of the test facility and converter is shown in figure 8. Preliminary performance results are being obtained.

Summary

The feasibility of constructing a heat-pipe heated and heat-pipe cooled thermionic converter that forms a representative module of an advanced space power system has been demonstrated. Several advances in the field of materials, heat transfer and electrode fabrication have been introduced that now provide reasonable performance and hold promise for performance growth.

References

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5. T. H. Pigford and B. E. Thinger, "Performance Characteristics of a 0001 Rhenium Thermionic Converter," Thermionic Specialist Conference (Oct. 1969).

6. NAS3-13231, Westinghouse Astronuclear Laboratory.

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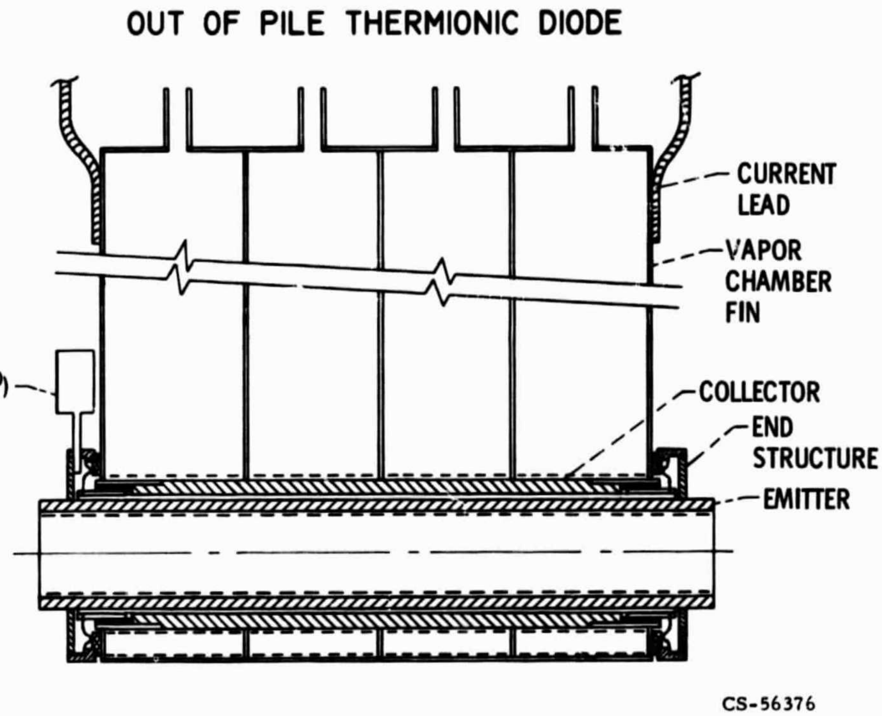

Figure 1. - Schematic - out of pile thermionic diode.

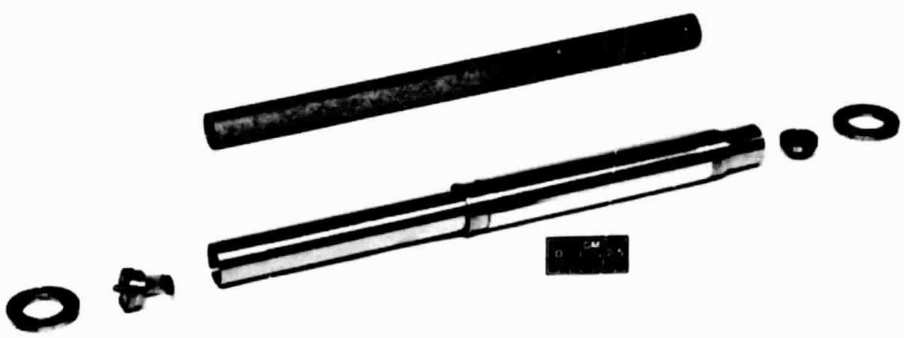

Figure 2. - Heat pipe-emitter components.

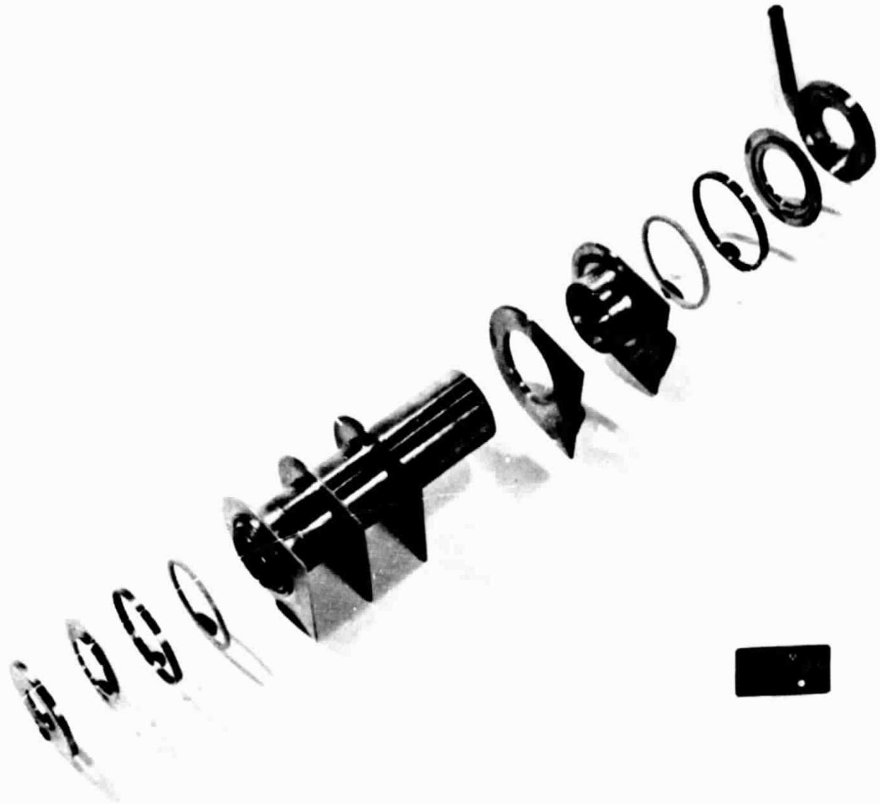

Figure 3. - Collector-end components (partially assembled).

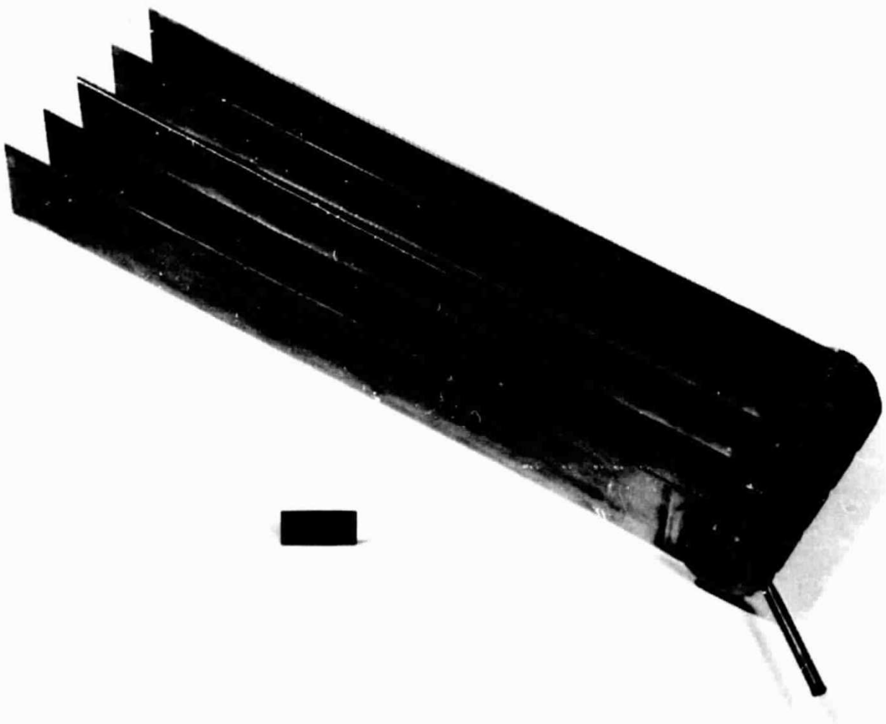

Figure 4. - Collector-end-vapor chamber fin assembly (shown without outer members).

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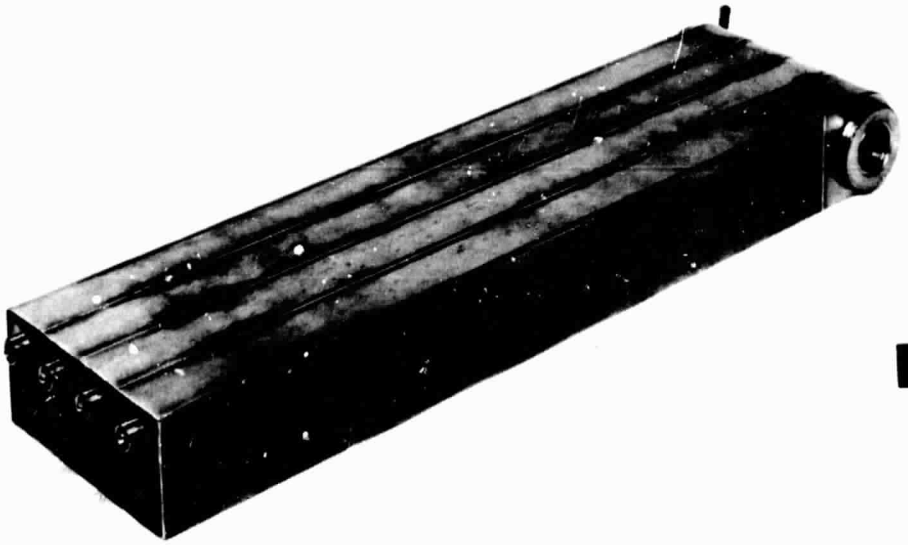

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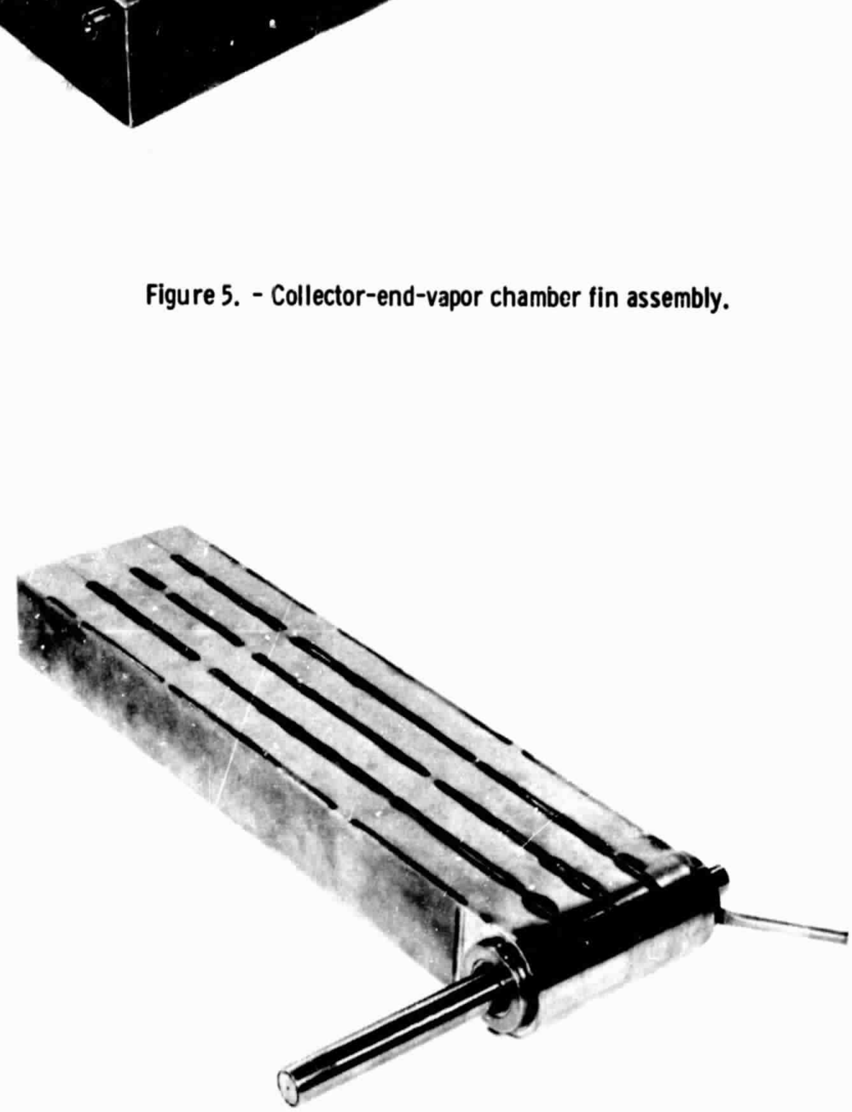
Figure 5. - Collector-end-vapor chamber fin assembly.



[redacted]

Figure 6. - Converter assembly.

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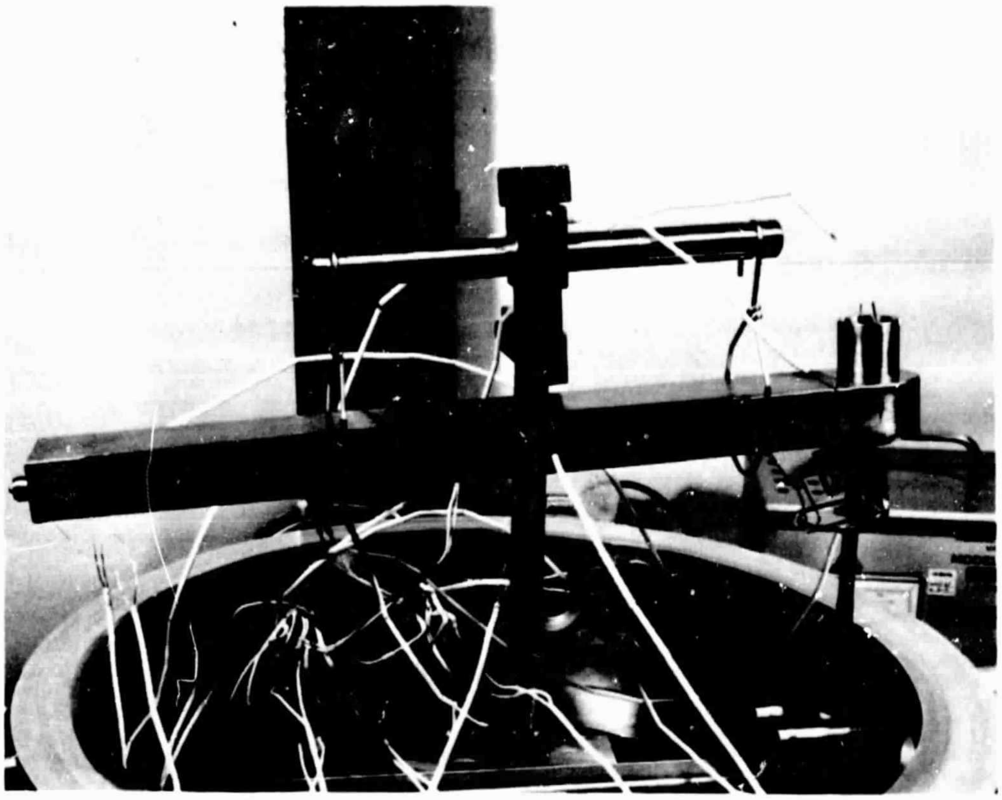

Figure 7. - Vapor chamber fin mock-up (in test fixture).

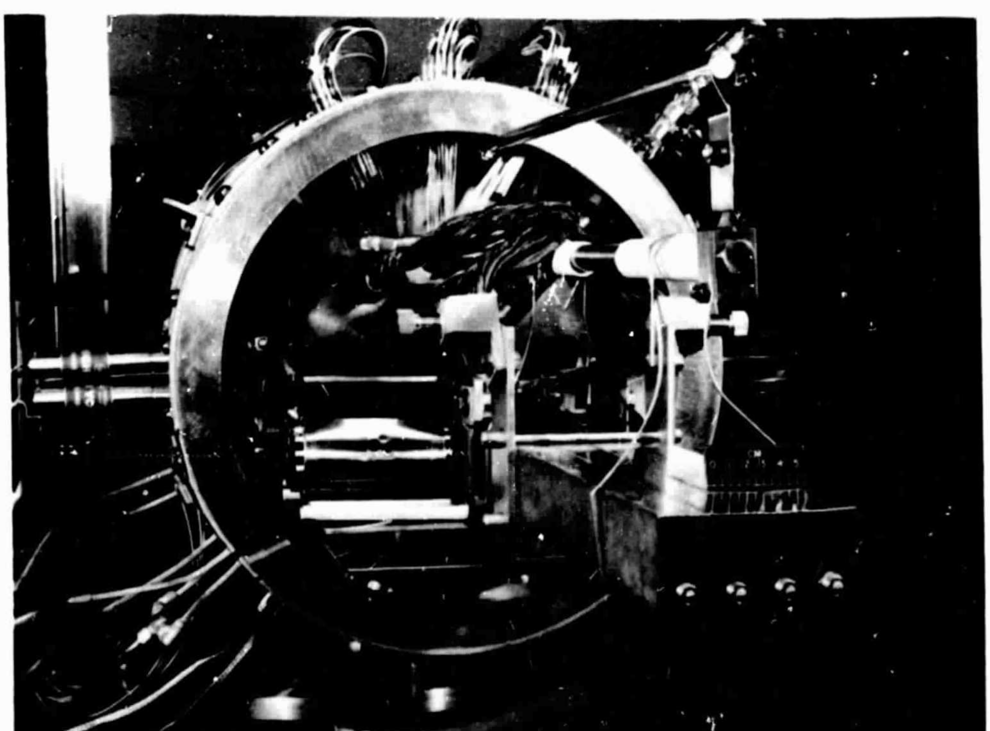

Figure 8. - Converter assembly (in test fixture).